(3) Describe what further experiments and modeling are needed to evaluate the use of solenoids versus quads for future WDM experiments

Art Molvik & HCX and NDCX Groups

the Heavy-Ion Fusion Science Virtual National Laboratory

(HIFS-VNL)

February 22, 2007

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HIFS e-cloud effort

HCX Experiment	NDCX Experiment	Simulation
Art Molvik	Peter Seidl	Jean-Luc Vay
Michel Kireeff Covo	Joshua Coleman	Bill Sharp
Frank Bieniosek	Prabir Roy	Ron Cohen
Peter Seidl	Frank Bieniosek	Alex Friedman
	Art Molvik	Dave Grote
		Steve Lund

Quads VS solenoids – two issues

(1) Maximum ion-beam current, and the associated emittance – in solenoids and quadrupole magnets

(2) Degradation of (1) by electron (and gas) cloud effects and their mitigation.

Quads VS solenoids – two issues

(1) Measure and model the maximum ion-beam current, and the associated emittance, which can be transported in solenoids and quadrupole magnets; and compare with theory (which predicts that significantly higher line charge can be transported at low energy in a solenoid). A subset of this is to measure Brillouin transport (or departures from it) in solenoids.

(2) Measure and model electron (and gas) cloud effects and determine how those affect the maximum beam current and emittance, degrade performance relative to electron (and gas)-free operation, and how well these effects can be mitigated.

Maximum ion-beam current, and the associated emittance – in solenoids and quadrupole magnets

- **Electrostatic quads: Lionel Prost – thesis, and Phys. Rev. Special Topics – Accelerators and Beams (PRSTAB) 8, 020101 (2005): Applications at low energy, clears e-clouds.**
- **Magnetic quads: Line charge increases with beam velocity**
- **Solenoids: Highest line charge at low energies – would like to observe Brillouin flow.**

Beam current and envelope agrees with envelope codes in each case: implies good agreement between experiment and theory.

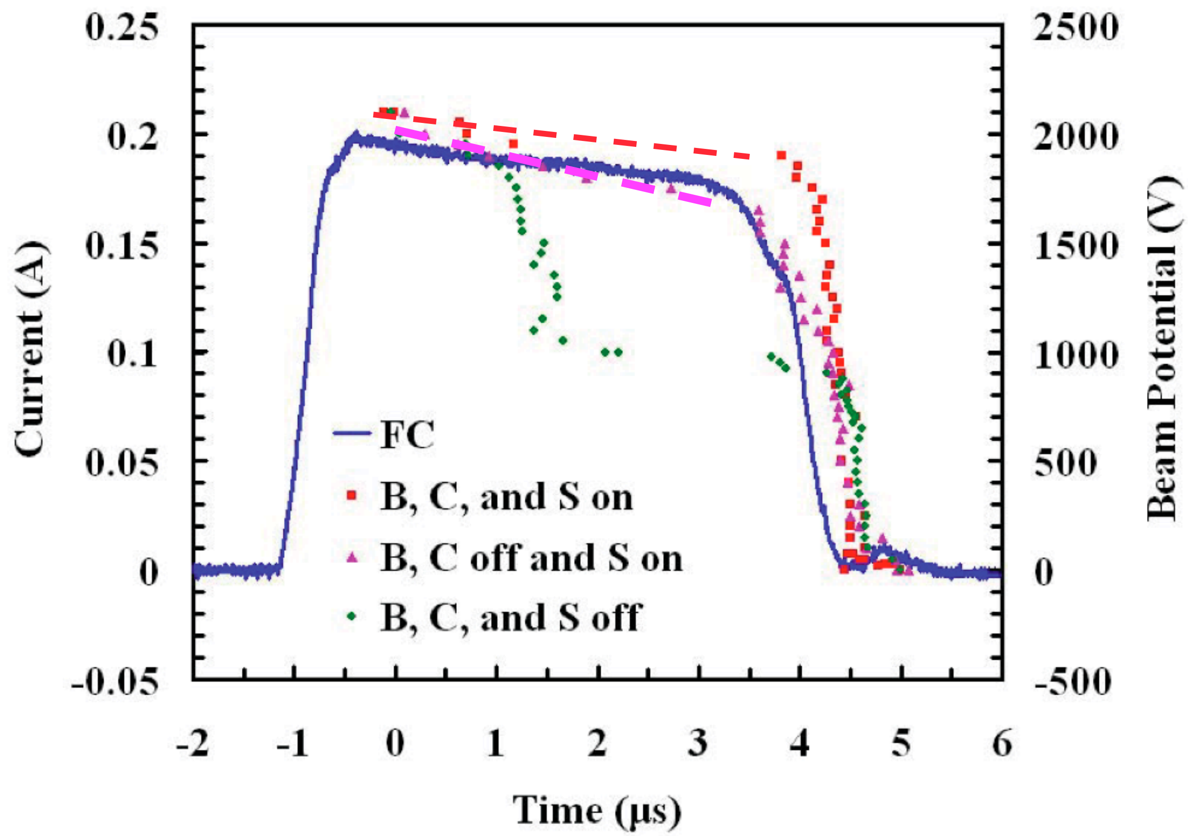
Theory: E. P. Lee, R. J. Briggs, "The solenoidal transport option: IFE drivers, near term research facilities, and beam dynamics," Report LBNL 40774, Sept. 1997.

Degradation of (1) by electron (and gas) cloud effects

- **Electrostatic quads: Clears e-clouds, ok if e- sources small**
- **Magnetic quads:**
  - **See effects at high e- line charge**
  - **Can measure e- line charge** [PRL **97**, 054801 (2006)]
  - **Need to determine thresholds for allowable electron charge from each type of source: ionization, beam-tube & end-wall emission.**
- **Solenoids:**
  - **See effects at high e- line charge**
  - **Need to measure e- line charge**
  - **Need to determine thresholds for allowable electron charge from each type of source: ionization, beam-tube & end-wall emission.**

1st measurement of absolute electron cloud density* – used retarding field analyzer (RFA) and clearing electrodes

- RFA measures max. expelled ion energy E_i (scan bias on successive pulses)
- $E_i = \phi_b$, max. beam potential
- ϕ_b depressed by electrons
- Clearing electrode current: infer minimum n_e, and corroborate higher n_e



Absolute electron fraction can be inferred from RFA and clearing electrodes

Beam neutralization	B, C, & S on	B, C, off S on	B, C, S off
Clear. Electr. A	~ 7%	~ 25%	~ 89%
RFA	(~ 7%)	~ 27%	~ 79%

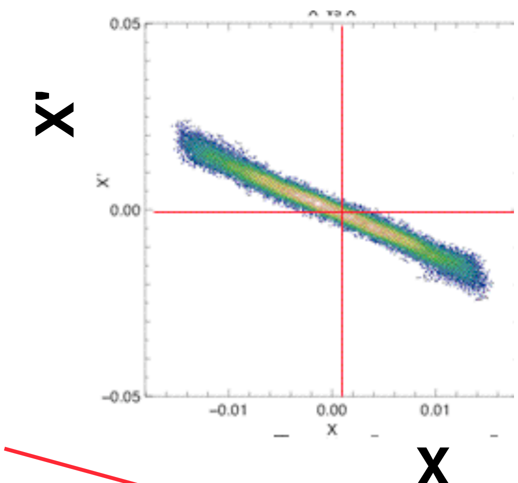
*Michel Kireeff Covo, Phys. Rev. Lett. 97, 054801 (2006).

Heavy-ion beams can be degraded by electron clouds

- Compact phase-space essential to a small focal spot

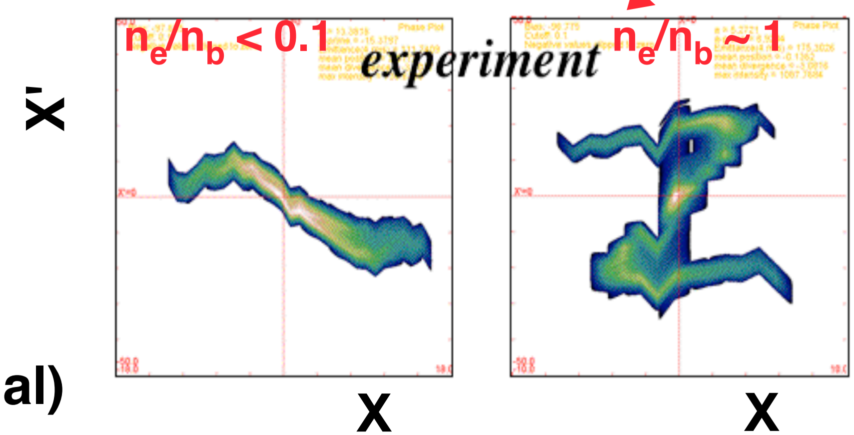
- Ideal beam has minimum phase space

Ideal



Artificially high electron density to exaggerate electron effects

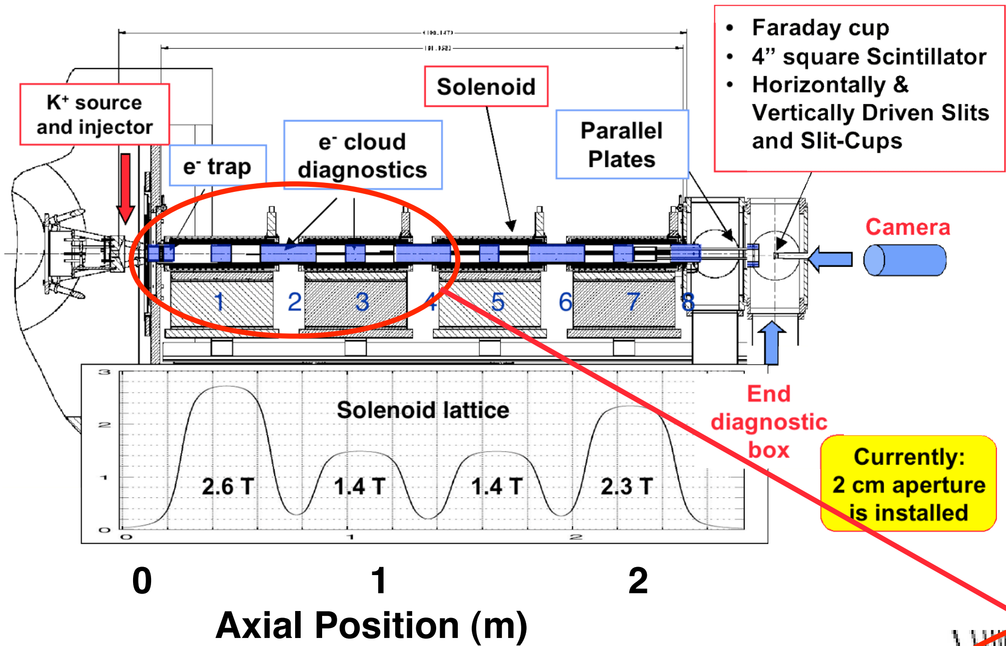
- Electrons can distort phase space, greatly increasing area of focal spot.



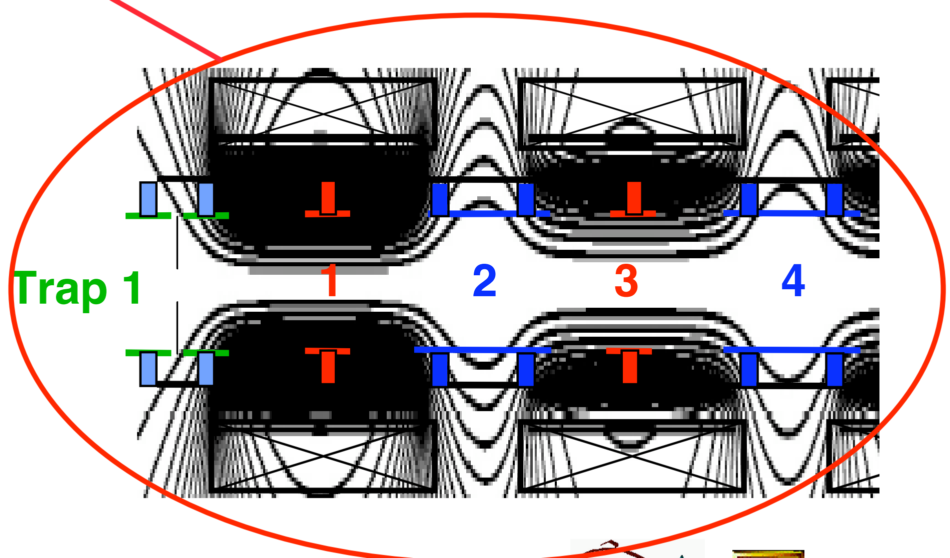
x = horizontal location of ion

x' = dx/dz of ion (transverse/axial)

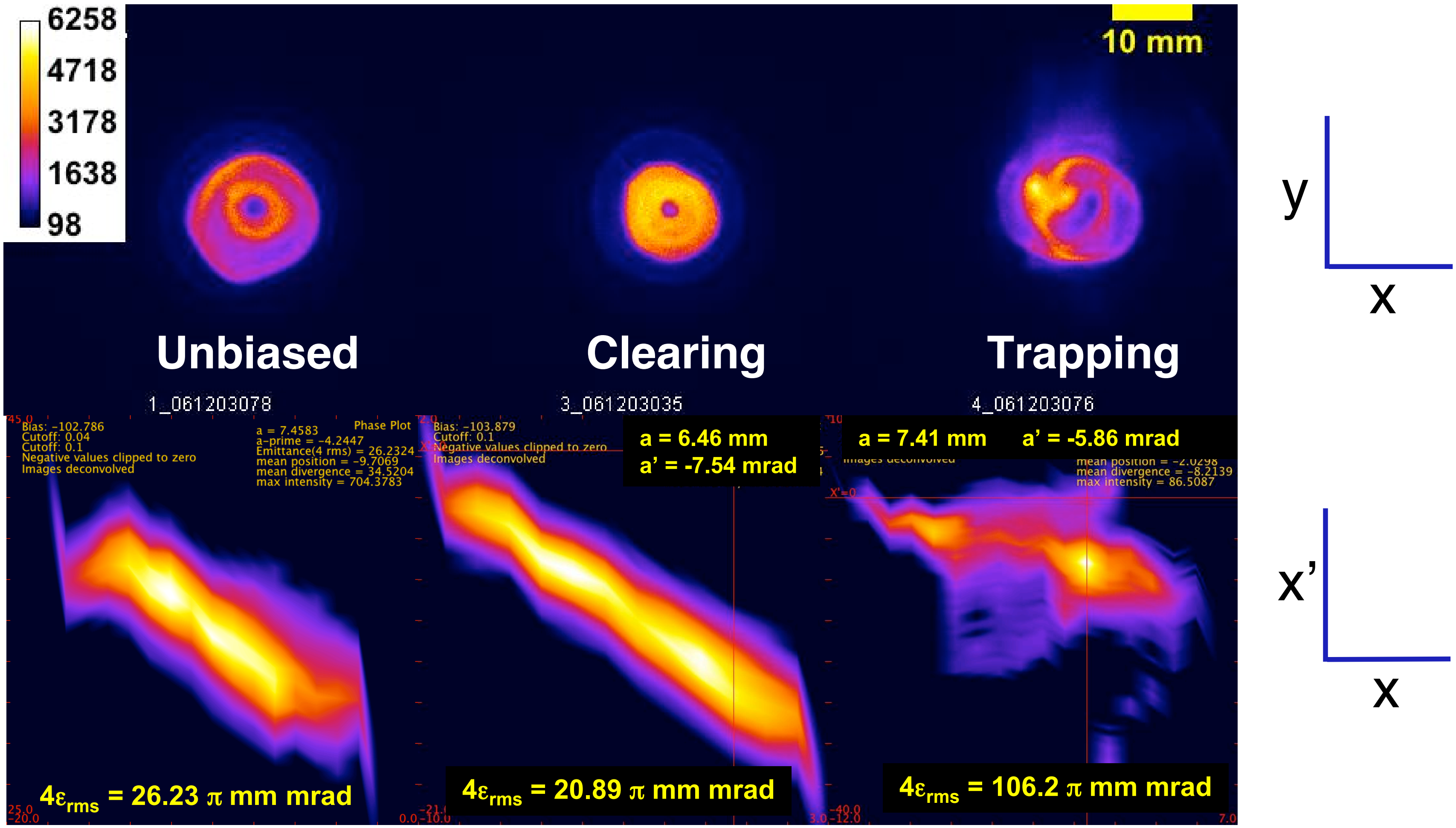
We have begun experiments studying e-clouds in solenoid magnets



Electrodes installed in center of each solenoid and between solenoids to provide control of e-emission and trapping on outer magnetic field lines.



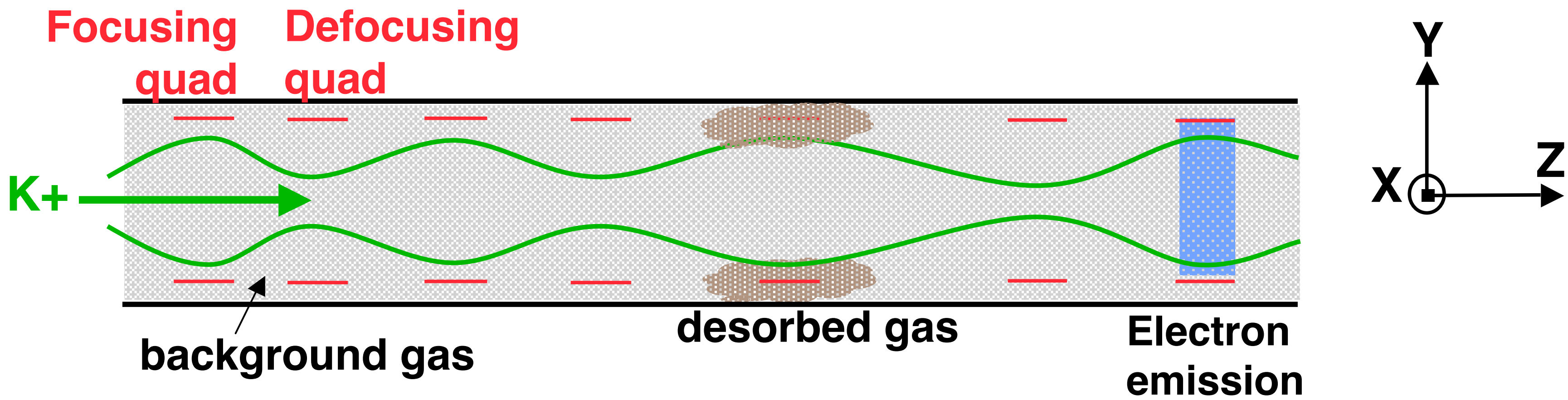
E-cloud electrode bias affects apertured beam quality



New accelerators for WDM and HIF must push performance to cost ratio, and guarantee successful operation

- Electron and gas physics likely to determine operating limits, e.g.:
  - Maximum beam current
  - Compactness - how close can beam tube approach beam?
  - Electron-ion instabilities (as seen in PSR)
- Devise mitigation techniques to increase limits
  - Clearing electrodes remove electrons
  - Roughened walls reduce electron and gas generation
  - Materials or coatings reduce electron and gas generation
  - Halo scraping by apertures reduces electron and gas generation

Control of accelerator beam-surface interactions is as important as control of MFE plasma-surface interactions

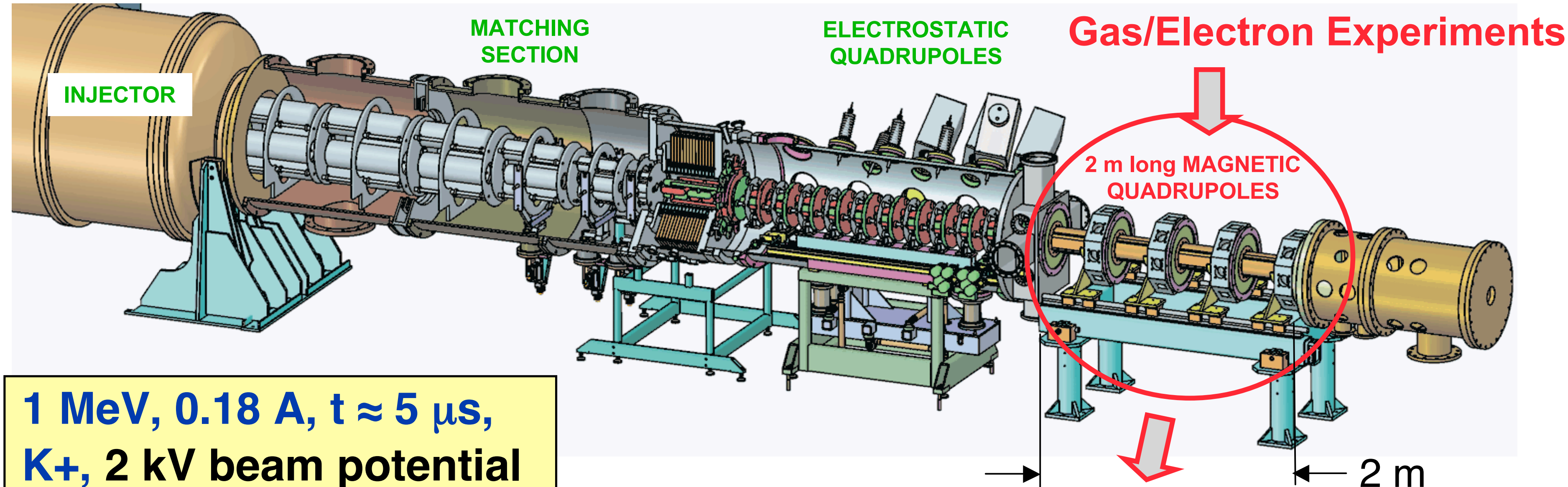


Charged particle beams transport efficiently with 'strong focusing', alternating gradient magnetic quadrupoles

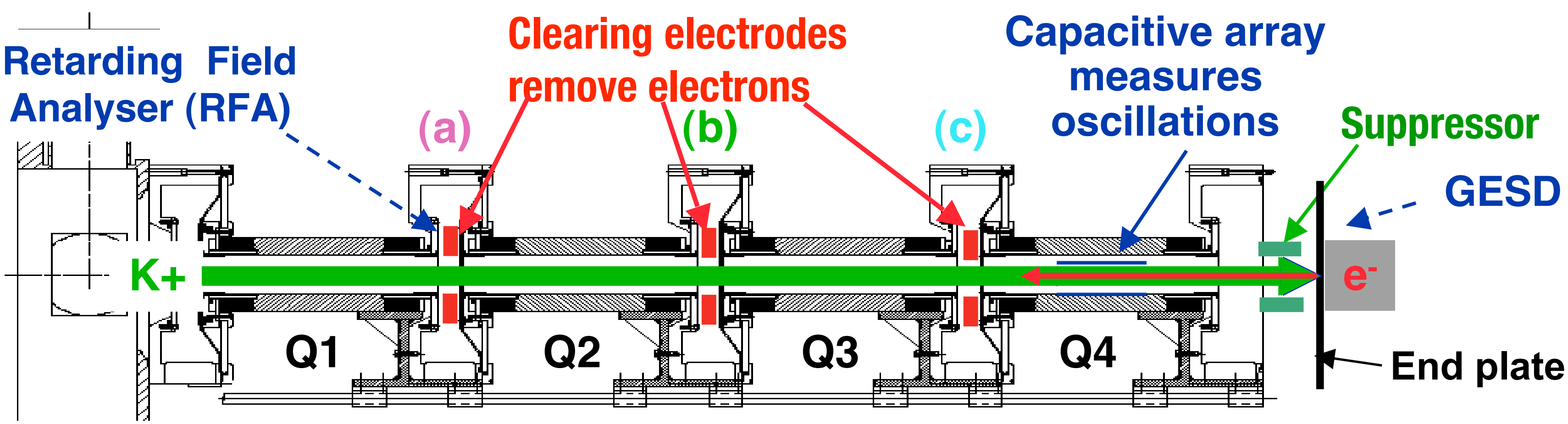
Primary:
- Ionization of background or desorbed gas
- Ion-induced gas & electron emission from
  - expelled ions hitting vacuum wall
  - beam halo scraping

Secondary:
- secondary emission from electron-wall collisions

The High Current Experiment (HCX) is a small, flexible heavy-ion accelerator (at LBNL)



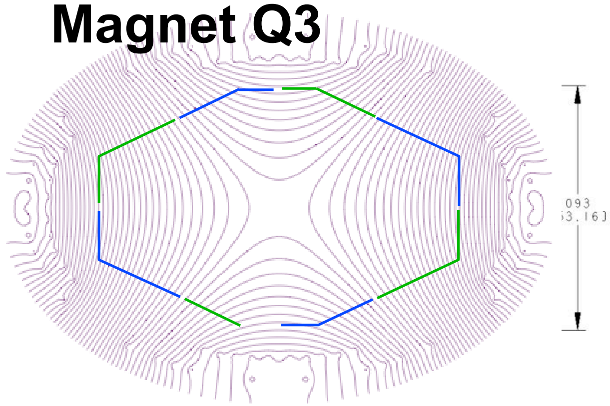
1 MeV, 0.18 A, t ≈ 5 μs,
K+, 2 kV beam potential



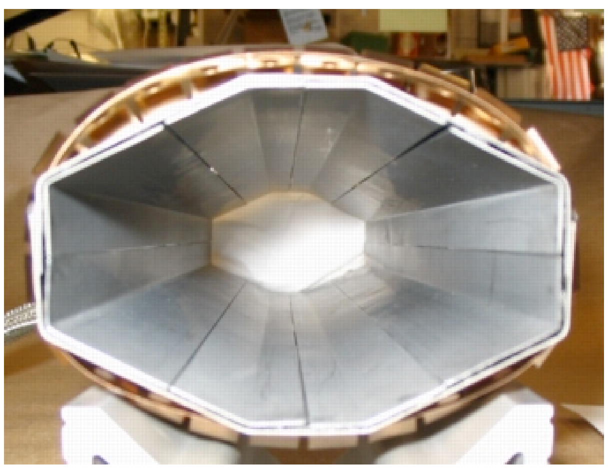
Quadrupole magnets Q1 - Q4 for beam transport

Diagnostics within magnetic quadrupole bores

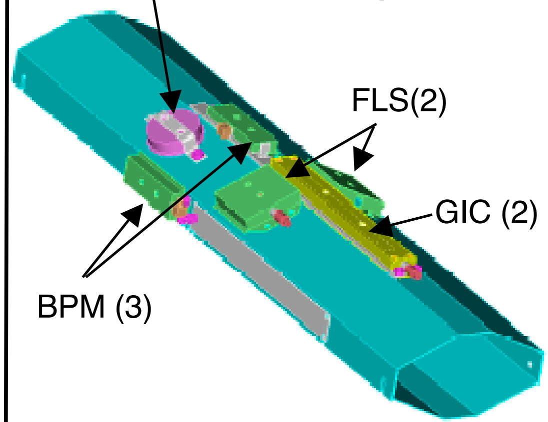
Magnet Q3

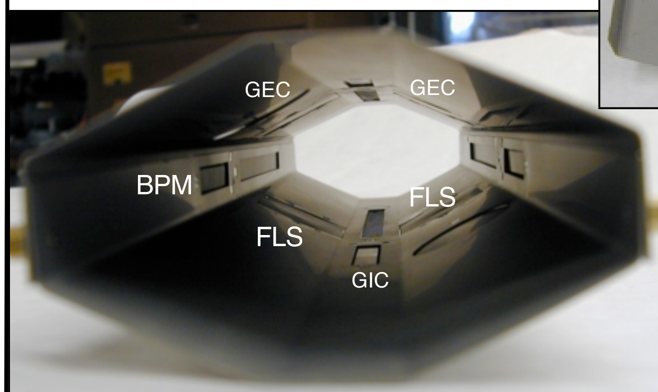


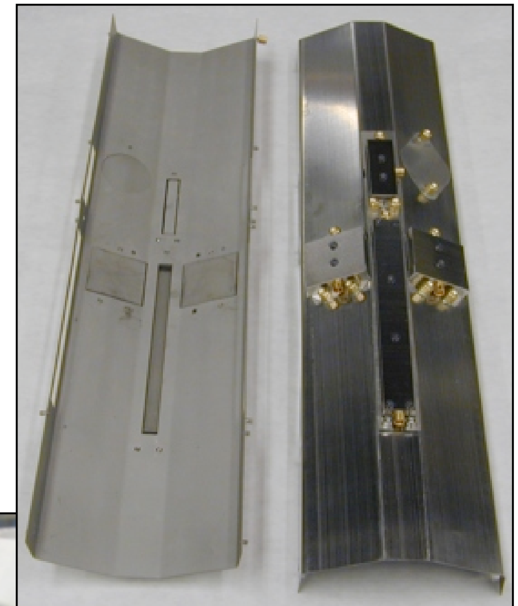
FLL: 8-biased electrodes at ends of field lines: measure capacitive signal + electrons from wall



Magnet Q4







Capacitive and grid-shielded electrodes

Outline

I. Mostly experiment

1. **Introduction and experimental tools**
2. **Beam-surface interactions**
3. **Absolute measurements of gas and e-**
4. **Plasma oscillations**

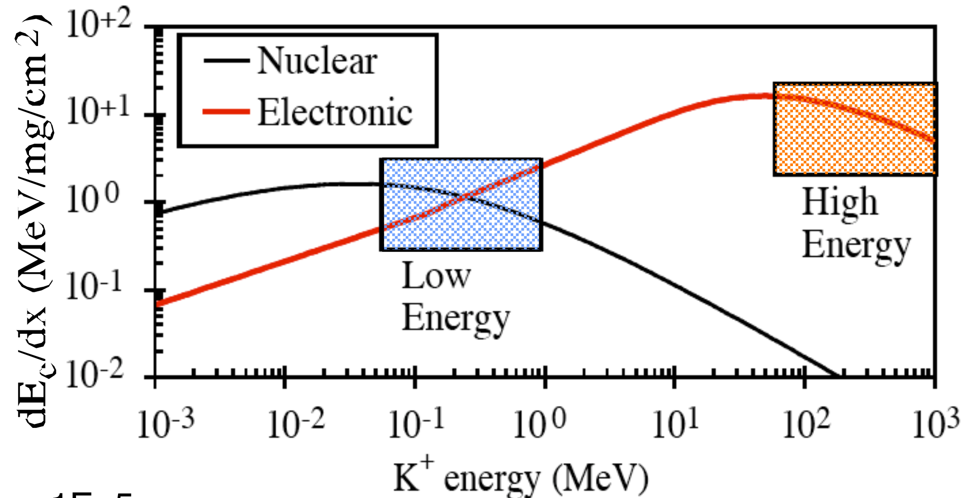
Electronic gas desorption scales with $(dE/dx)^2$, like electronic sputtering

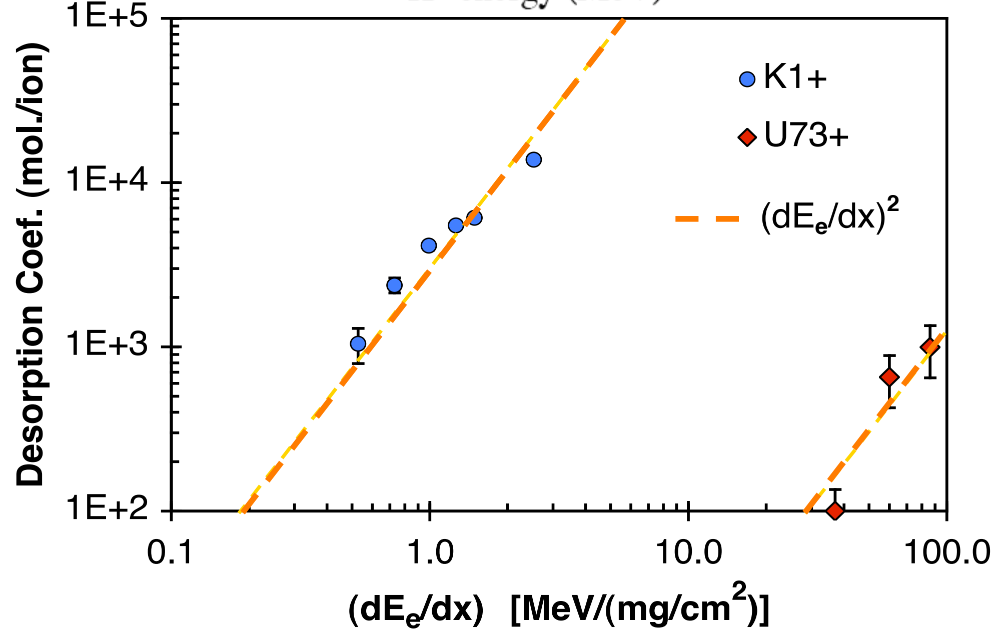
Conventional sputtering driven by large-angle nuclear scattering

Electronic sputtering more copious.

- **Well known for ions onto thick insulating layers,**
- **Scales with $(dE_e/dx)^n$ where $1 \le n \le 3$.**

Electronic desorption, n ≈ 2.





Molvik, et al., PRL ~2/9/07

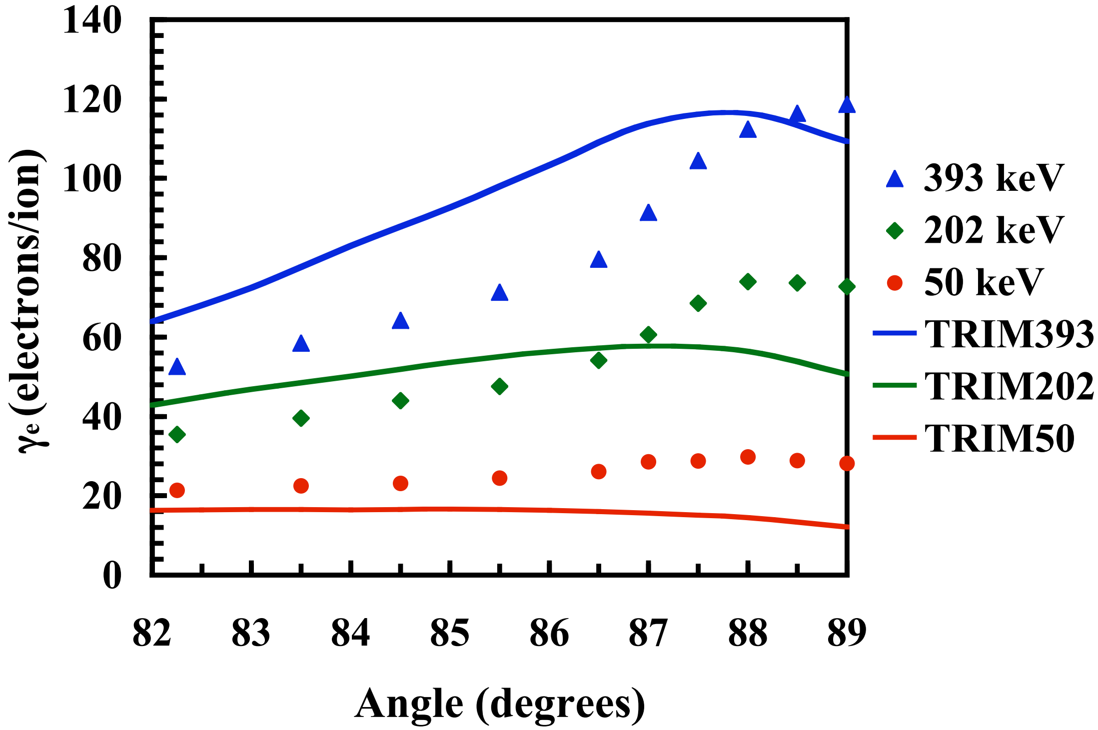
Developed model for ion-induced electron yield scaling with beam energy and angle of incidence*

Model electron yield (electrons/ion) versus

- ion energy
- angle of incidence

Reasonable agreement with our measurements

Not 1/cosθ at these lower ion energies



Modified Sternglass model**
evaluated with TRIM code

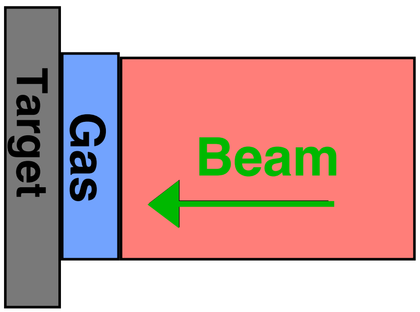
$$\gamma_e \propto \frac{\delta}{\cos(\theta)}\left(\frac{dE}{dx}\right)_e$$

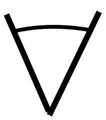
* Michel Kireeff Covo, PRSTAB 9, 063201 (2006).

** E. J. Sternglass, Phys. Rev. 108, 1 (1957).

We measure velocity distribution of desorbed gas

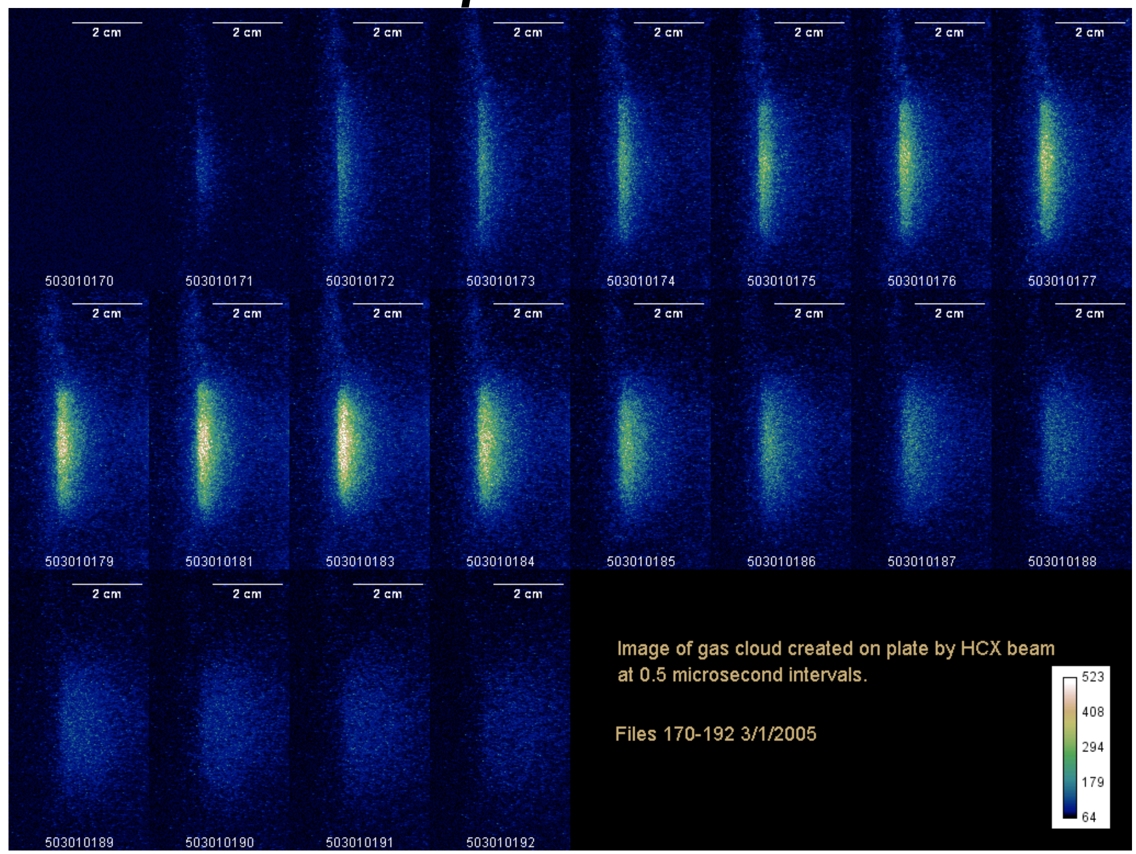
Observation: desorbed gas in beam emits light





View expanding gas cloud from side – $f(v_0)$ normal to target [with gated camera]

0.5 μs intervals F. Bieniosek

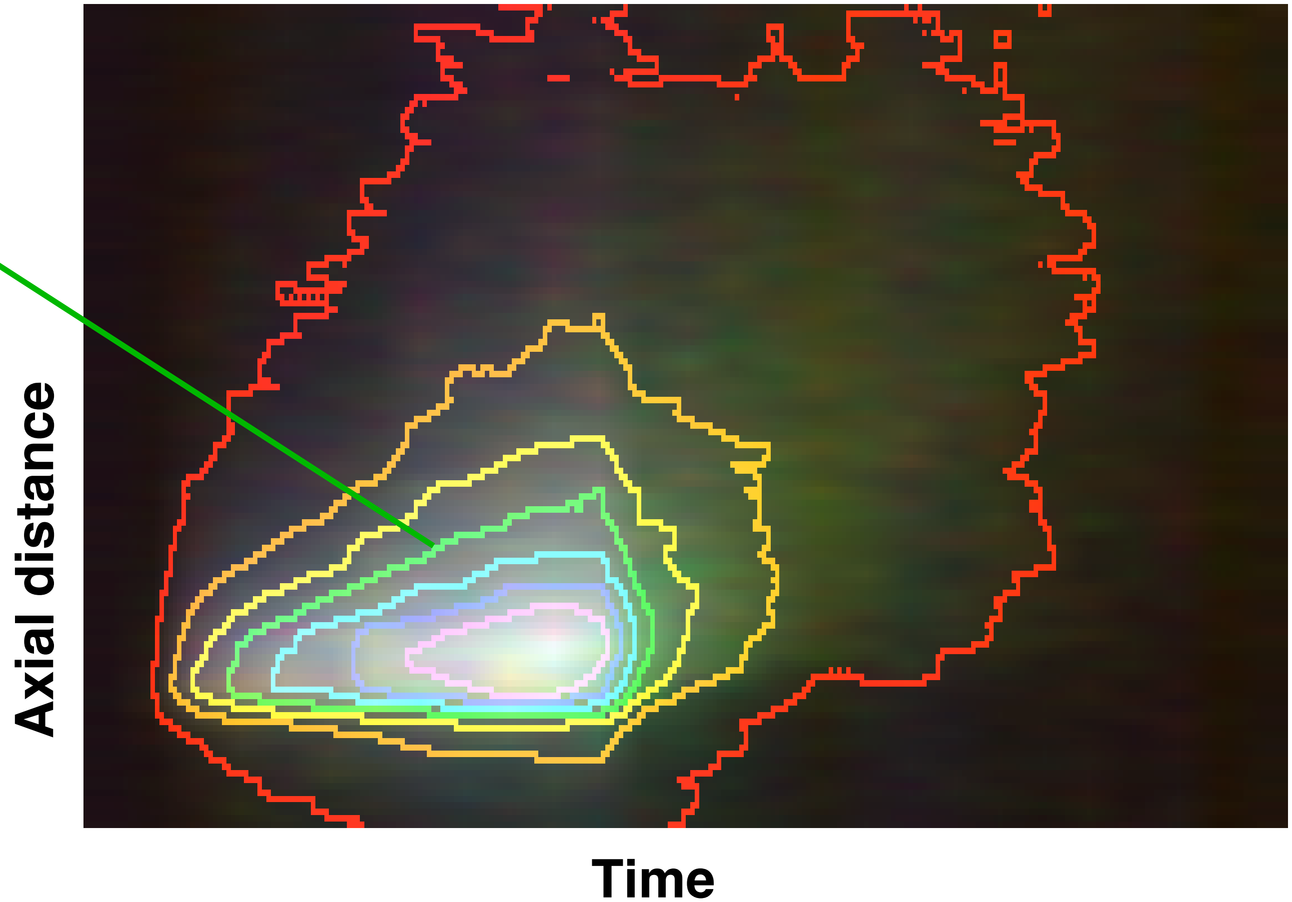


Future – absolutely calibrate camera to determine desorption yield, apply technique to non-evaporable getter (NEG)

Line integral of images indicates an expansion velocity of up to a few mm/μs

Estimated velocity:
Slope ~1 mm/μs

Corresponds to room temperature H_2, consistent with residual gas measurements



Outline

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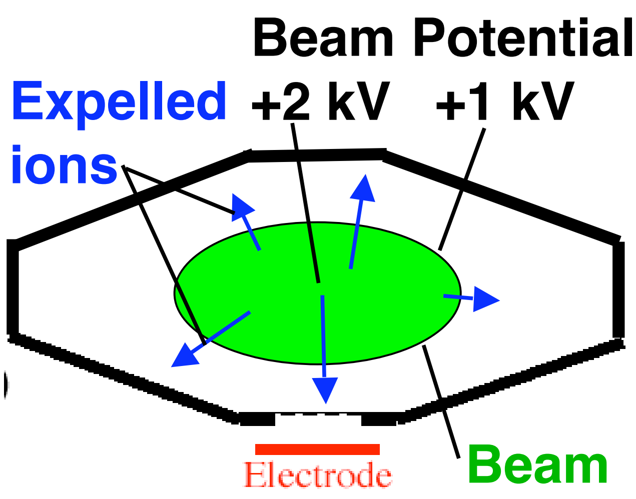
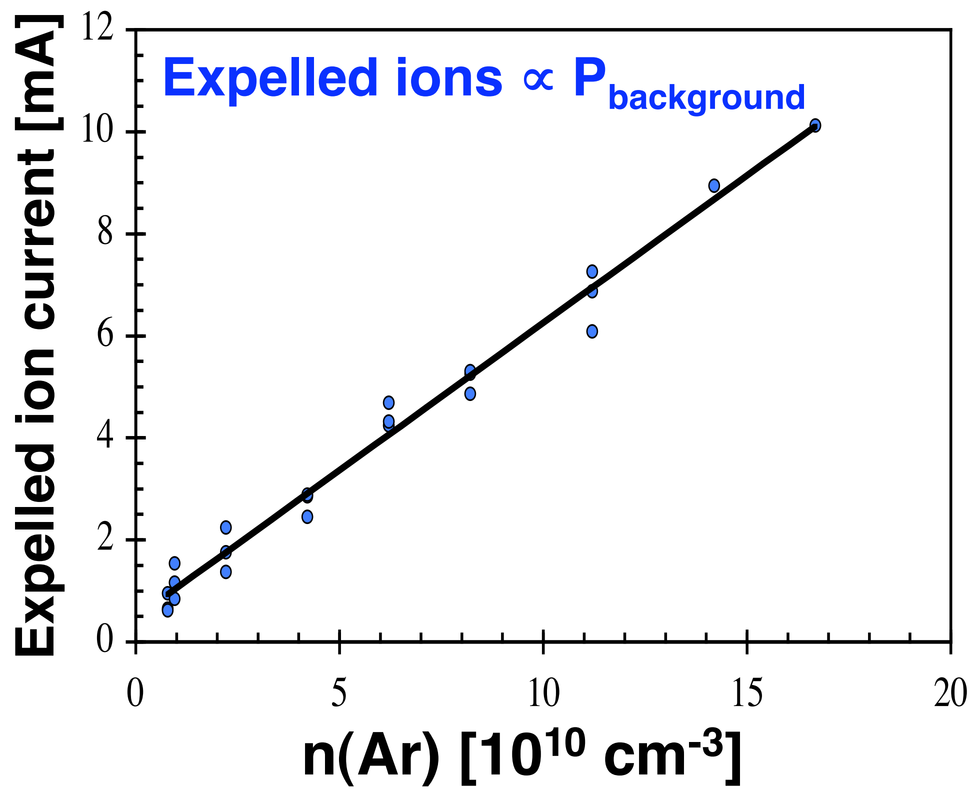
4. Plasma oscillations

II. Mostly theory and simulation

We measure electron sources – ionization

1. Ionization of gas by beam ($n_e/n_b \leq 3\%$)



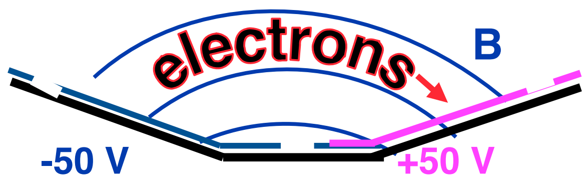


Beam current known; from expelled ion current infer

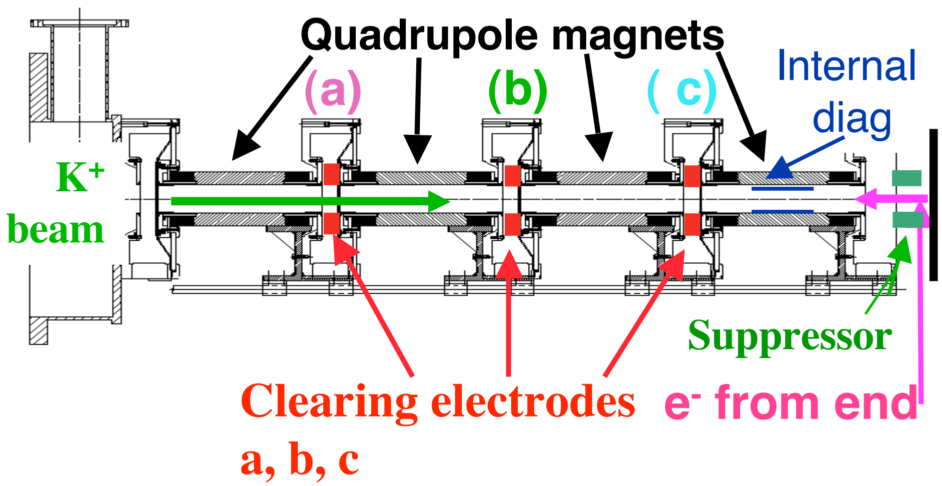
- Ionization rate
- Also, gas density in beam

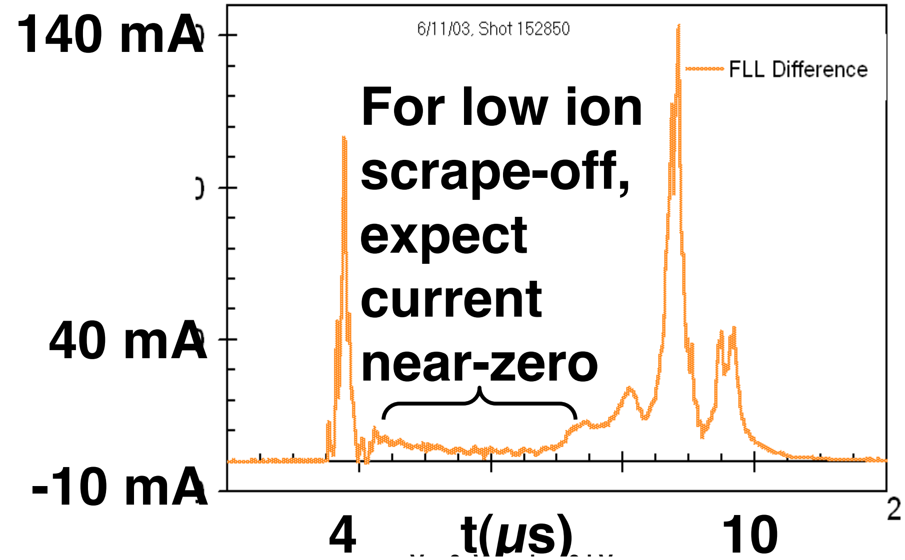
We measure electron sources – walls

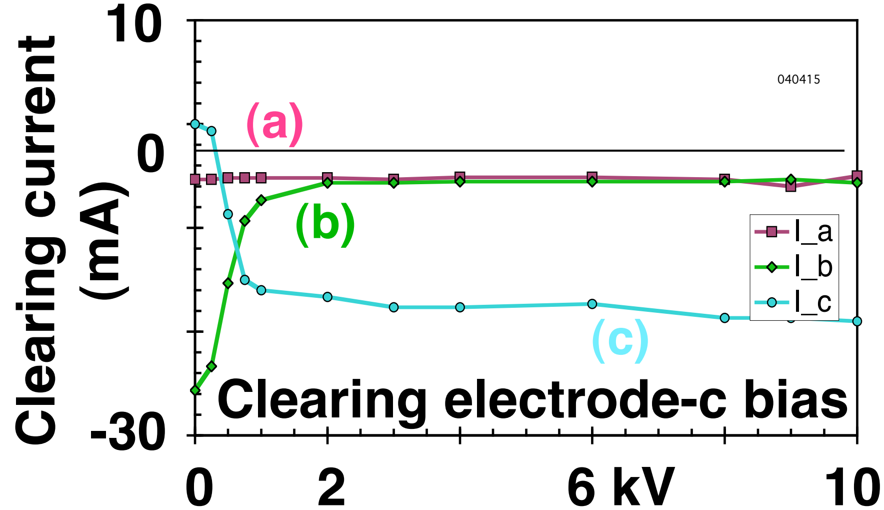
2. **Electron emission – beam tube** ($n_e/n_b \leq 7\%$)



3. **Electron emission – end wall** (n_e/n_b, 0, 100%)







Outline

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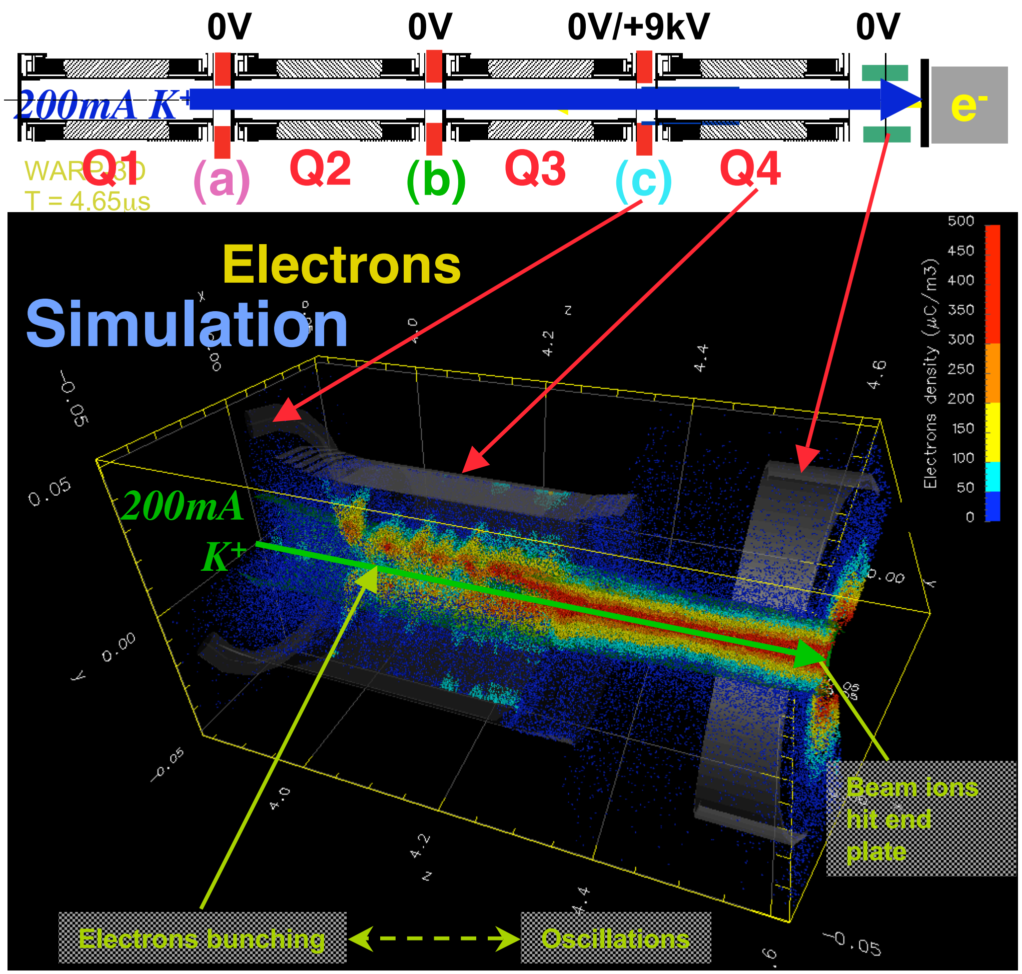
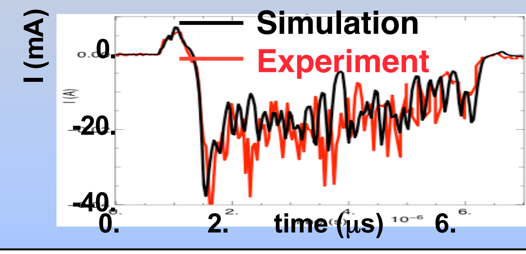
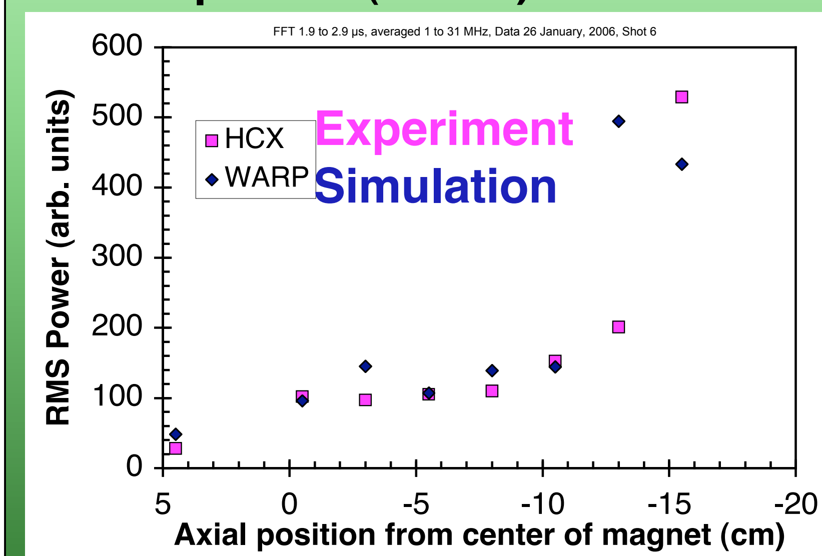
Electron oscillations – simulation & experiment agree



Current to clearing electrode (c) agrees in frequency ~ 6 MHz



Currents to capacitive electrode array agree in wavelength ~5 cm, and amplitude (below)



Summary – We have established a sound basis to understand and mitigate electrons and gas

- **Increased understanding of beam-surface interactions**
  - **Electron emission measured and modeled, $\propto dE_e/dx$**
  - **Discovered gas desorption ~ $(dE_e/dx)^2$**
- **Major electron sources measured:**
  - **Wall emission from beam-scrape-off dominates (~7%) +gas**
  - **End-wall emission suppressed to ~0% (if not suppr. ~80%)**
  - **Gas ionization small (~3%)**
- **Absolute measurement of e- accumulation as function of time**
- **Electrons bunch, generating oscillations**
  - **Simulation & experiment agree – freq., wavelength, & amplitude**
  - **Experimental validation of simulations provides credibility**